CS 406: Syntax Directed Translation

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- Syntax-directed translation → the source language translation is completely driven by the parser
  - The parsing process and parse trees/AST used to direct semantic analysis and the translation of the source program
  - Separate phase of a compiler or grammar augmented with information to control the semantic analysis and translation (attribute grammars)
- Attribute grammars → associate attributes with each grammar symbol
  - An attribute has a name and an associated value: string, number, type, memory location, register — whatever information we need.
  - Examples
    - Attributes for a variable include type (as declared, useful later in type-checking)
    - An integer constant will have an attribute value (used later to generate code)
- With each grammar rule we also give semantic rules or actions, describing how to compute the attribute values associated with each grammar symbol in the rule
  - An attribute value for a parse node may depend on information from its children nodes, its siblings, and its parent

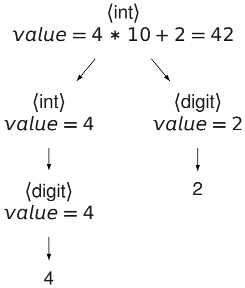
Grammar			Action(s)
$\langle\text{int}\rangle$	$::=$	$\langle\text{digit}\rangle$	$\{\langle\text{int}\rangle_0.\mathit{value} = \langle\text{digit}\rangle.\mathit{value};\}$
	$\mid$	$\langle\text{int}\rangle\langle\text{digit}\rangle$	$\{\langle\text{int}\rangle_0.\mathit{value} = \langle\text{int}\rangle_1.\mathit{value} * 10 + \langle\text{digit}\rangle.\mathit{value};\}$
$\langle\text{digit}\rangle$	$::=$	0	$\{\langle\text{digit}\rangle.\mathit{value} = 0;\}$
	$\mid$	1	$\{\langle\text{digit}\rangle.\mathit{value} = 1;\}$
	$\mid$	2	$\{\langle\text{digit}\rangle.\mathit{value} = 2;\}$
	...		
	$\mid$	9	$\{\langle\text{digit}\rangle.\mathit{value} = 9;\}$

- Attributes are computed during the construction of the parse tree and are typically included in the node objects of that tree
- Two general classes of attributes:
  - Synthesized: passed up in the parse tree
  - Inherited: passed down the parse tree

ATTRIBUTES

- Synthesized attributes: the left hand-side attribute is computed from the right hand-side attributes

$$\begin{array}{rcl} X & ::= & Y_1\, Y_2 \ldots Y_n \\ X.a & = & f(Y_1.a, Y_2.a, \ldots, Y_n.a) \end{array}$$



  - The lexical analyzer supplies the attributes of terminals
  - The attributes for nonterminals are built up for the nonterminals and passed up the tree

- Inherited attributes: the right hand-side attributes are derived from the left hand-side attributes or other right hand-side attributes

$$\begin{array}{rcl} X & ::= & Y_1\, Y_2 \ldots Y_n \\ Y_k.a & = & f(X.a, Y_1.a, Y_2.a, \ldots, Y_{k-1}.a, Y_{k+1}.a, \ldots, Y_n.a) \end{array}$$

  - Used for passing information about the context to nodes further down the tree

Attributes (cont'd)

$\langle P \rangle$	$::=$	$\langle D \rangle \langle S \rangle$	$\{\langle S \rangle.dl = \langle D \rangle.dl;\}$
$\langle D \rangle$	$::=$	$var\ \langle V \rangle\ ;\ \langle D \rangle$	$\{\langle D \rangle_0.dl = \text{addList}(\langle V \rangle.name, \langle D \rangle_1.dl);\}$
	$\mid$	ε	$\{\langle D \rangle_0.dl = \text{NULL};\}$
$\langle S \rangle$	$::=$	$\langle V \rangle\ := \langle E \rangle\ ;\ \langle S \rangle$	$\{\text{check}(\langle V \rangle.name, \langle S \rangle_0.dl); \langle S \rangle_1.dl = \langle S \rangle_0.dl;\}$
	$\mid$	ε	$\{\}$
$\langle V \rangle$	$::=$	x	$\{\langle V \rangle.name = "x";\}$
	$\mid$	y	$\{\langle V \rangle.name = "y";\}$
	$\mid$	z	$\{\langle V \rangle.name = "z";\}$

$$
\begin{array}{llll}
\langle P\rangle & ::= & \langle D\rangle\langle S\rangle & \{\langle S\rangle.\mathit{dl} = \langle D\rangle.\mathit{dl};\} \\
\langle D\rangle & ::= & \mathit{var}\ \langle V\rangle\ ;\ \langle D\rangle & \{\langle D\rangle_0.\mathit{dl} = \text{addList}(\langle V\rangle.\mathit{name}, \langle D\rangle_1.\mathit{dl});\} \\
 & \mid & \varepsilon & \{\langle D\rangle_0.\mathit{dl} = \text{NULL};\} \\
\langle S\rangle & ::= & \langle V\rangle\ := \langle E\rangle\ ;\ \langle S\rangle & \{\text{check}(\langle V\rangle.\mathit{name}, \langle S\rangle_0.\mathit{dl}); \langle S\rangle_1.\mathit{dl} = \langle S\rangle_0.\mathit{dl};\} \\
 & \mid & \varepsilon & \{\} \\
\langle V\rangle & ::= & x & \{\langle V\rangle.\mathit{name} = "x";\} \\
 & \mid & y & \{\langle V\rangle.\mathit{name} = "y";\} \\
 & \mid & z & \{\langle V\rangle.\mathit{name} = "z";\}
\end{array}
$$

- Two attributes: *name* for the name of the variable and *dl* for the list of declarations

$$
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 & | & \varepsilon & \{\} \\
\langle V\rangle & ::= & x & \{\langle V\rangle.name = "x";\} \\
 & | & y & \{\langle V\rangle.name = "y";\} \\
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\end{array}
$$

- Two attributes: *name* for the name of the variable and *dl* for the list of declarations
- Each time a new variable is declared a synthesized attribute for its name is attached to it
- That name is added to a list of variables declared so far in the synthesized attribute *dl* created from the declaration block

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\begin{array}{llll}
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- Each time a new variable is declared a synthesized attribute for its name is attached to it
- That name is added to a list of variables declared so far in the synthesized attribute *dl* created from the declaration block
- The list of variables is then passed as an inherited attribute to the statements following the declarations so that it can be checked that variables are declared before use

ATTRIBUTES (CONT'D)

- Most programming languages require both synthesized and inherited attributes
- A given style of parsing favors attribute flow in one direction
  - Top-down parsing deals trivially with inherited attributes
  - Bottom-up parsing deals trivially with synthesized attributes
  - The other direction is handled using other techniques
  - For example, a symbol table is often used to pass attributed back and forth irrespective of the direction favored by any particular parsing method

Attribute Implementation

- Typically handling of attributes: associate with each symbol either member variables in the AST node structure or some sort of structure (e.g., list) with all the necessary attributes
  - If we have a list then we store it as a member variable in each node structure
- Associate code to the processing of each nonterminal to carry on the attribute computations
- Also need some convention for referring to individual symbols in a rule while defining the associated action
  - Typical convention in compiler generators: `$$` to refer to the left hand side and `$i` to refer to the `i`-th component of the right hand side:

```
P -> DS          { $$.list = $1.list; }
D -> var V; D    { $$.list = add_to_list($2.name, $4.list); }
   |             { $$.list = NULL; }
S -> V := E; S   { check($1.name, $$.list); $5.list = $$.list; }
   |
V -> x           { $$.name = "x"; }
   | y           { $$.name = "y"; }
   | z           { $$.name = "z"; }
```

- Consider a LR parser ready to reduce using $\langle \text{A} \rangle ::= X_1 \ldots X_n$
- The synbols X_i are on the stack before the reduction
- Previous reductions have associated semantic values (attributes) to these symbols
- They are then popped and $\langle \text{A} \rangle$ is pushed in their place
- While we do this, we execute some code that compute the attribute valued for $\langle \text{A} \rangle$
- In effect we have a syntactic stack (for the actual parsing) and a semantic stack (for the semantic values)

Issues in Bottom-up Syntax Directed Translation

$$\begin{array}{rcl}\langle\text{digit}\rangle & ::= & 0 \mid 1 \mid \ldots \mid 9 \\ \langle\text{int}\rangle & ::= & \langle\text{digit}\rangle \mid \langle\text{int}\rangle\langle\text{digit}\rangle \\ \langle\text{num}\rangle & ::= & o\ \langle\text{int}\rangle \mid \langle\text{int}\rangle\end{array}$$

- We require that the *o*-prefixed numbers be evaluated in octal

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- We require that the *o*-prefixed numbers be evaluated in octal
- Drawback: no restriction to octal digits for octal numbers
- Major drawback: not enough information from below for the differentiation between decimal and octal numbers
  - Semantic rules for computing these are different, yet they should all get attached to the rules for ⟨int⟩
  - The decision on whether to process a decimal or octal number happens when *o* is shifted on the stack
  - At that time however an ⟨int⟩ has already been reduced and so its semantic actions have already been applied
  - In addition, semantic rules can only be applied to reductions, not shifts

First Solution: Rule Cloning

- Since our problem is caused by using the same rules for two different things, we can clone those rules so that we have separate copies for separate purposes
- When to use one set of rules and when to use the other is given based on the context of the nonterminal (i.e., where is the nonterminal used)

$$
\begin{aligned}
\langle\text{digit}\rangle &::= 0 \mid 1 \mid \ldots \mid 9 \\
\langle\text{int}\rangle &::= \langle\text{digit}\rangle \mid \langle\text{int}\rangle\langle\text{digit}\rangle \\
\langle\text{intOct}\rangle &::= \langle\text{digit}\rangle \mid \langle\text{intOct}\rangle\langle\text{digit}\rangle \\
\langle\text{num}\rangle &::= o\ \langle\text{intOct}\rangle \mid \langle\text{int}\rangle
\end{aligned}
$$

- Drawback: Grammar inflation
  - The added rules are not meaningful syntactically
- Extreme care should be taken when modifying a grammar to make sure that the new version still generates the same language
  - The problem of context-free grammar equivalence is undecidable

Second Solution: Forcing Semantic Actions

- Suppose we need a semantic action when shifting some token x
  - We can insert a new rule $\langle \mathrm{A} \rangle ::= x$, and attach the action to this rule
  - All the occurrences of x in the original grammar will be replaced by $\langle \mathrm{A} \rangle$
- Suppose we need a semantic action between two symbols x and y

Second Solution: Forcing Semantic Actions

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  - We can insert a new rule $\langle \text{A} \rangle ::= x$, and attach the action to this rule
  - All the occurrences of x in the original grammar will be replaced by $\langle \text{A} \rangle$
- Suppose we need a semantic action between two symbols x and y
  - We then insert a new rule $\langle \text{A} \rangle ::= \varepsilon$ and attach the action to it
  - All the occurrences of x y in the original grammar will be replaced by $x \langle \text{A} \rangle y$

$$
\begin{array}{rcll}
\langle \text{num} \rangle & ::= & \langle \text{oct} \rangle \ \langle \text{int} \rangle & \{ ans = \langle \text{int} \rangle.value; \} \\
 & \mid & \langle \text{dec} \rangle \ \langle \text{int} \rangle & \{ ans = \langle \text{int} \rangle.value; \} \\
\langle \text{oct} \rangle & ::= & o & \{ base = 8; \} \\
\langle \text{dec} \rangle & ::= & \varepsilon & \{ base = 10; \} \\
\langle \text{int} \rangle & ::= & \langle \text{digit} \rangle & \{ \langle \text{int} \rangle_0.value = \langle \text{digit} \rangle.value; \} \\
 & \mid & \langle \text{int} \rangle \langle \text{digit} \rangle & \{ \langle \text{int} \rangle_0.value = \langle \text{int} \rangle_1.value * base + \langle \text{digit} \rangle.value; \} \\
\langle \text{digit} \rangle & ::= & 0 & \{ \langle \text{digit} \rangle.value = 0; \} \\
 & \ldots & & \\
 & \mid & 9 & \{ \langle \text{digit} \rangle.value = 9; \}
\end{array}
$$

- Note the use of the global variable *base* (common occurrence)
- The same caveats about modifying the grammar (semantic-only rules, equivalence) apply

Third Solution: Grammar Restructuring

- Global variables are undesirable because rules may be recursive and this may have unexpected consequences on these variables
  - Global variables can also make the semantic actions difficult to write and maintain since there is a lack of separation between actions
  - Proper initialization and resetting may be problematic
- A more robust solution is to restructure the parse tree as to eliminate the need for global variables:
  1. Sketch a parse tree that allows bottom-up synthesis without global variables
  2. Revise the grammar to achieve that parse tree
  3. Verify that the grammar is still suitable for parsing ($LALR(1)$, etc.)
  4. Verify that the grammar still generate the same language

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$$
\begin{array}{rcll}
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& & & \ \langle\text{int}\rangle_0.\mathit{base} = \langle\text{int}\rangle_1.\mathit{base};\}\\
& | & \langle\text{base}\rangle & \{\langle\text{int}\rangle_0.\mathit{base} = \langle\text{base}\rangle.\mathit{base};\ \langle\text{int}\rangle_0.\mathit{value} = 0;\}\\
\langle\text{base}\rangle & ::= & \varepsilon & \{\langle\text{base}\rangle.\mathit{base} = 10;\}\\
& | & o & \{\langle\text{base}\rangle.\mathit{base} = 8;\}\\
\langle\text{digit}\rangle & ::= & 0 & \{\langle\text{digit}\rangle.\mathit{value} = 0;\}\\
& \ldots & & \\
& | & 9 & \{\langle\text{digit}\rangle.\mathit{value} = 9;\}
\end{array}
$$

Top-Down Syntax Directed Translation

- Top-down parsers are usually recursive descent parsers
- The computation of attributes is naturally inserted in the code, just like the code for constructing the AST
  - Same ideas as above may be required to modify the grammar so that all the attributes can be computed

```
class Node {...};

Node* Sequence() {
    Node* current = new Node(SEQ, ...);
    if (t == CLS_BRACE) /* <empty> */ ;
    else { /* <statement> <sequence> */
        current.addChild(Statement());
        current.addChild(Sequence());
    }
    return current;
}
```

- Also see the example in the textbook

- The most common semantic actions are the ones that construct the abstract syntax tree for the input program
  - AST is a simplified and more compact representation of the parse tree
  - Just like in a parse tree, an AST node can have an arbitrary number of children
  - Links to the parent often needed (depending on the algorithms used in the semantic analysis)
- The data structure for an AST node can be approached in two ways
  1. Have individual types for individual nodes (assignment, conditional, loop, etc.) → see assignments
     - Handy for languages that provide type definitions with inheritance, case in which this is the preferred method
     - Awkward in languages that do not offer inheritance constructs

ABSTRACT SYNTAX TREES

- The most common semantic actions are the ones that construct the abstract syntax tree for the input program
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- The data structure for an AST node can be approached in two ways
  1. Have individual types for individual nodes (assignment, conditional, loop, etc.) → see assignments
     - Handy for languages that provide type definitions with inheritance, case in which this is the preferred method
     - Awkward in languages that do not offer inheritance constructs
  2. Have the same data structure for all nodes
     - General, language-independent solution
     - Needs efficient representation for nodes with arbitrary number of children
     - Typical implementation: left-child-right-sibling
       Each node is a node in a binary tree
       The "left child" of a node points to the first child of that node
       The "right child" of a node points to the next (right) sibling of that node

AST Design Principles

- AST design is crucial for the next phases of the compilation process
- It should be possible to reconstitute ("unparse") the program from an AST
  - An AST node must hold enough information to recall the program fragment that generated it
- Subsequent phases of the compilation process must access the AST through suitable interfaces
  - Different phases have different requirements (and so will use different interfaces)
  - Several phases will modify AST nodes
  - It is crucial to provide proper encapsulation to ensure that the AST information is not altered inadvertently
- Subsequent compilation phases will traverse the AST (possibly repeatedly)
  - The easiest way to accomplish this is through polymorphic and recursive functions defined within the class hierarchy of AST node
    - The functions must be virtual to ensure the proper application for each node type
  - Most useful pattern for such functions: visitors $\rightarrow$ traverse the whole tree recursively